Systems & Control Transactions

**Research Article - Peer Reviewed Conference Proceeding**
ESCAPE 35 - European Symposium on Computer Aided Process Engineering
Ghent, Belgium. 6-9 July 2025
Jan F.M. Van Impe, Grégoire Léonard, Satyajeet S. Bhonsale,
Monika E. Polańska, Filip Logist (Eds.)

PSE PRESS

# Cost-effective Process Design and Optimization for Decarbonized Utility Systems Integrated with Renewable Energy and Carbon Capture Systems

**Haryn Park[a], Joohwa Lee[a], Bogdan Dorneanu[b], Harvey Arellano-Garcia[b]*, and Jin-Kuk Kim[a]***

[a] Hanyang University, Department of Chemical Engineering, Seoul, Republic of Korea
[b] Brandenburg University of Technology Cottbus - Senftenberg, Process and Plant Technology, Cottbus, Germany
* Corresponding Authors: arellano@b-tu.de, jinkukkim@hanyang.ac.kr

## ABSTRACT

Industrial decarbonization is considered one of the key objectives in mitigating global climate change. To achieve a net-zero industry requires actively transitioning from fossil fuel-based energy sources to renewable alternatives. However, the intermittent nature of renewable energy sources poses challenges to a reliable and robust supply of energy for industrial sites. Therefore, the integration of renewable energy systems with existing industrial processes, subject to energy storage solutions and main grid interconnections, is essential to enhance operational reliability and overall energy resilience. This study proposes a novel framework for the design and optimization of industrial utility systems integrated with renewable energy sources. A monthly-based analysis is adopted to consider variable demand and non-constant availability in renewable energy supply. Moreover, carbon capture is considered in this work as a viable decarbonization measure, which can be strategically combined with renewable-based electrification. The proposed optimization model evaluates the economic trade-offs of integrating carbon capture, renewable energy, and energy storage. By applying this approach, systematic design guidelines are developed for the transition of a conventional steady-state utility system toward renewable energy integration, ensuring economically viable and sustainable energy management in process industries.

**Keywords**: Renewable energy, CO2 capture, Industrial utility operation, Cost optimization, Process integration

## INTRODUCTION

The International Energy Agency (IEA) estimates that the industrial sector, including power generation, accounts for a major portion of overall $CO_2$ emission [1]. Therefore, the 2030 targets for industrial energy consumption focus on increasing the share of electricity while reducing reliance on fossil fuels. In particular, electricity generated from renewable sources is identified as a key solution to achieve environmental improvements in the industrial sector.

In South Korea, where most energy supply systems rely on fossil fuel-based facilities, the integration of renewable energy systems with existing infrastructure for process utility enhances system operational stability by addressing the intermittency of renewable energy sources. Additionally, carbon capture technology, as the additional solution of industrial decarbonization, can complement existing fossil fuel-based utilities by reducing environmental burdens [2], while helping to resolve potential challenges that may occur during the transitional period to complete process integration. However, previous studies on the optimization of integrated energy supply systems often fail to fully account for the flexibility and/or constraints associated with renewable energy production. In many cases, the power demand of the utility systems is met through electricity imported from external plants for renewable electricity, rather than reflecting the complexity of direct integration [3]. Furthermore, the impact of $CO_2$ emitted from fossil fuels in the integrated process is often oversimplified as a carbon tax without considering the potential role and benefits of incorporating carbon capture processes.

This study proposes integrating conventional utility systems with $CO_2$ capture processes and renewable energy systems, including electricity storage, as a practical approach for industrial decarbonization. A cost-based optimization framework is developed as a monthly-based analysis to evaluate strategies for the economically efficient operation of the integrated process. Monthly minimum costs are determined using weather data specific to South Korea, allowing for more accurate cost predictions in renewable electricity generation and enhancing the reliability of the optimization model.

## METHODOLOGY

To achieve an environmentally upgraded utility system, the integration of renewable energy and carbon capture processes is optimized with the objective function, as given in Eq. (1), of minimizing overall system costs while meeting practical energy demands as outlined in **Table 1**.

$$f_{Total,Min} = f_{Utility,Min} + f_{Renewable,Min} \qquad (1)$$

Steam demand is supplied exclusively by fossil fuel-based systems, with the low-pressure (LP) steam demand allowed to vary during process optimization, while steam requirements for other pressure levels remain fixed at constant values. Electricity demand can be met either through the integrated system or by purchasing it from external sources, depending on the specific scenario evaluated. The process flow diagram illustrating the overall system in this study is described in **Figure 1**.

**Table 1:** Energy demand of a Total site.

| Energy | Unit | Values |
|---|---|---|
| Electricity | $MW_e$ | Min. 68.0 |
| VHP steam | t/h | 20.0 |
| HP steam | t/h | 54.5 |
| MP steam | t/h | 55.9 |
| LP steam | t/h | $128.0 + \alpha^*$ |

The costing parameters used to calculate the annualized cost of each system are based on previous studies [3, 5]. For renewable facilities, the cost references were adjusted by scaling down costs according to the GDP ratio to account for the differences in economic contexts between South Korea and the UK, from which the original data was derived. The cost-related values applied in this study are summarized in **Table 2**.

### Utility Process

The fossil fuel-based utility system uses a traditional configuration with boilers and gas turbines (GT) paired with heat recovery steam generators (HRSG), followed by electricity generation via steam turbines (ST). In line with current industrial trends, coal and natural gas are selected as the primary fuel sources for steam and electricity production. The system meets four different steam demands at varying pressure levels, as outlined in **Table 1**. Residual steam is used to generate electricity via back-pressure steam turbines. For simplicity, the fossil fuel-based facility is represented using a streamlined model developed in UniSim®, as referenced previously in [3].

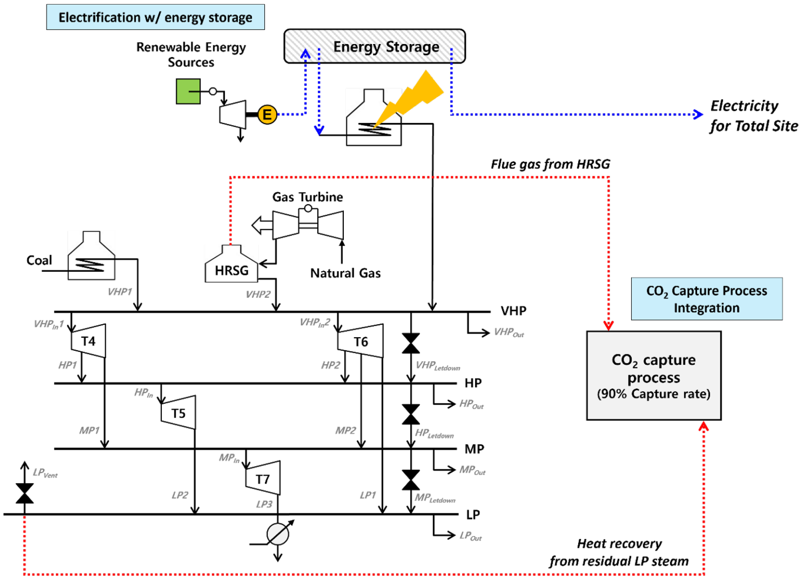

**Figure 1:** Simplified process flow diagram of the utility system integrated with renewable energy supply and carbon capture.

**Table 2:** Costing parameters considering the site location for the integrated utility process.

| Parameters | Unit | Description | Values |
|---|---|---|---|
| $C_{coal}$ | \$/t | Coal price | 65 |
| $C_{NG}$ | \$/t | Natural gas price | 220 |
| $NHV_{coal}$ | kJ/kg | Net heating value of coal | 28,000 |
| $NHV_{NG}$ | kJ/kg | Net heating value of Natural gas | 47,206 |
| $C_{elec,ex}$ | \$/kWh | Electricity price (Export) | 0.067 |
| $C_{elec,im}$ | \$/kWh | Electricity price (Import) | 0.081 |
| $C_{water}$ | \$/t | Water price | 0.005 |
| $CP_{PV}$ | \$/kW | PV capital cost | 781.3 |
| $OP_{variable,PV}$ | \$/kWh | PV variable O&M cost | 0.004 |
| $OP_{fixed,PV}$ | \$/kW/yr | PV fixed O&M cost | 9.8 |
| $CP_{WT}$ | \$/kW | WT capital cost | 3156.4 |
| $OP_{variable,WT}$ | \$/kWh | WT variable O&M cost | 0.5 |
| $OP_{fixed,WT}$ | \$/kW/yr | WT fixed O&M cost | 23.4 |
| $CP_{EST}$ | \$/kW | EST capital cost | 421.9 |
| $OP_{variable,EST}$ | \$/kWh | EST variable O&M cost | 0.004 |
| $n$ | yr | Plant lifetime | 30 |
| $r$ | % | Interest rate | 12 |
| $CR$ | kgCO₂/kWh | CO₂ emission from renewable system | 0.254 |
| $CT$ | \$/tCO₂ | Carbon tax | 20 |

The optimization framework of the utility steady-state operation is formulated with the objective function of minimizing system costs. This includes the operating costs from fuel consumptions, capital costs for conventional equipment, and carbon tax, and is described by:

$$f_{Utility,Min} = f_{OP,Utility} + f_{CP,Utility} + f_{CT,Utility} \quad (2)$$

$$f_{OP,Utility} = C_{coal} f_{coal}(m_{coal}) + C_{NG} f_{NG}(m_{NG}) + C_{water} Q_{condensor\ for\ BFW} \quad (3)$$

$$f_{CP,Utility} = f_{Boiler} + f_{GT} + f_{HRSG} + f_{ST} \quad (4)$$

$$f_{CT,Utility} = CT f_{coal}(m_{coal}) NHV_{coal} + 10^{-3} CT f_{NG}(m_{NG}) NHV_{NG} \quad (5)$$

Each term in the objective function is determined based on the optimized fuel consumption which can be calculated as a function of VHP steam mass flowrate ($m_{coal}$, $m_{NG}$) generated from each fuel. Specifically, the capital cost function is calculated using the capacity of each piece of equipment, which also reflects fuel consumption. As a result, major variables for minimizing fossil fuel-based processes are the quantities of coal and natural gas consumed. This optimization is carried out using the UniSim® optimization tool, incorporating the parameters, constraints, and boundaries outlined in [3].

For the flue gas emitted from the HRSG by natural gas, a conventional Monoethanolamine (MEA)-based $CO_2$ capture process, commonly used for post-combustion capture, is considered as referenced for capturing $CO_2$ from the NGCC plant [5]. A percentage of 90% of $CO_2$ is captured, with the remaining $CO_2$, including the flue gas from a coal-fired boiler, subject to a carbon tax penalty.

The primary optimization variable for the capture process is the thermal energy consumed by the stripper reboiler, typically supplied as LP steam generated by the utility. The LP steam demand for the capture process varies depending on the optimization of natural gas consumption. Therefore, the fluctuation in LP steam demand by the capture process is also considered in the optimization of the integrated utility as $\alpha^*$ in **Table 1**, although the operating and capital costs of the capture process are not reflected. The thermal energy demands of each month for the capture process are optimized in UniSim®.

## Renewable Process

Renewable electricity is generated using weather data of South Korea, solar irradiation ($I_{solar}$) for the photovoltaic (PV) system and wind speed ($v_{WT}$) for the wind turbine (WT) system. Monthly generated power is calculated from the accumulated observational data and system operating time ($T_{PV}$, $T_{WT}$), followed by calculating the system costs, including the carbon tax. Cost minimization of renewable energy is carried out by optimizing the capacity of each system. For PV and WT systems, the plant area ($A_{PV}$, $A_{WT}$) is considered for the optimization to determine the cost-based electricity production.

To address the irregular nature of renewable energy sources, an electricity storage (EST) system is introduced to supply power as needed. Hence, storage utilization for the overall site demand depends on the renewable energy available each month. The maximum storage capacity is limited to 5 MWₑ to reduce uncertainty during the optimization process, helping to identify the most cost-efficient operating conditions. When electricity exceeds this capacity, the surplus can be sold to the main grid connected to the site, generating additional revenue. Based on the costing parameters outlined in **Table 2**, the objective function considers all the costing elements of the renewable system from Eq. (6) to (11). In Eq. (9) and (10), $i$ which can be PV, WT, and EST is used to simplify the costing equations.

$$f_{Renewable,Min} = f_{OP,Ren} + f_{CP,Ren} + f_{CT,Ren} \quad (6)$$

$$P_{PV} = \frac{\sum_t 0.5\eta_{PV}A_{PV}I_{solar}(1-COS(34.5))}{T_{PV}} \quad (7)$$

$$P_{WT} = \frac{\sum_t 0.5\eta_{WT}A_{WT}{v_{WT}}^3}{T_{WT}} \quad (8)$$

$$f_{OP,Ren} = \sum_i (P_i OP_{fixed,i}/8760 + P_i OP_{variable,i}) - \begin{cases} C_{elec,im}P_{Grid}, & P_{Grid} < 0 \\ C_{elec,ex}P_{Grid}, & P_{Grid} > 0 \end{cases} \quad (9)$$

$$f_{CP,Ren} = \sum_i P_i CP_i \frac{r(1+r)^n}{(1+r)^n - 1} \quad (10)$$

$$f_{CT,Ren} = 10^{-3} CRCT(P_{PV} + P_{WT}) \quad (11)$$

The modeling and optimization of the renewable process are conducted using MATLAB® due to the data-driven nature of the process, which is more challenging to visualize compared to the fossil fuel-based process. A mathematical approach facilitates system cost optimization, providing valuable support for comprehensive strategic decision-making, particularly in complex, interdependent processes. This approach also has the advantage of being easily integrated with existing simulation software.

The optimization methodology for the integrated utility system is illustrated in **Figure 2**, which explains the overall applicable scenarios, including electricity generation, storage, and selling beyond the site through the main grid linked with the processes. This utility management can be explained by Eq. (12) and (13), which represents the key energy balance, including electricity storage, by adjusting the equations in previous studies [3, 4]. Moreover, inequality constraints required for the cost minimization are shown in **Table 3**. Especially, the boundaries of PV and WT system capacity serve to ensure that each system is optimized within an industrially feasible range based on the weather conditions.

$$P_{Utility} + P_{Renewable} - P_{Grid} - 68 = 0 \quad (12)$$

$$P_{Renewable} - (P_{PV} + P_{WT} - P_{EST}) = 0 \quad (13)$$

**Table 3:** Inequality constraints for the Integrated utility process optimization.

| Variable | Unit | Low bound | Upper bound |
|---|---|---|---|
| HP1 | t/h | 15 | - |
| MP2 | t/h | 30 | - |
| LP2 | t/h | 0 | - |
| $LP_{out}$ | t/h | $128+\alpha$ | - |
| Steam letdown | t/h | 0 | - |
| PV system capacity ($A_{PV}$) | $m^2$ | 0 | 100,000 |
| WT system capacity ($A_{WT}$) | $m^2$ | 0 | 100,000 |
| Renewable electricity to Total site ($P_{Renewable}$) | $MW_e$ | 0 | 68 |
| Grid electricity ($P_{Grid}$) | $MW_e$ | - | 68 |
| EST capacity ($P_{EST}$) | $MW_e$ | 0 | 5 |

## RESULTS AND DISCUSSION

The variations in renewable resources is analyzed from weather data to ensure that only available renewable energy applicable within the operating range allowed is utilized. Therefore, PV system considers its operating time to be limited to daylight hours, and WT system considers cut-in and cut-out speed for the feasible system operation according to the reference [4]. Considering these constraints, **Figure 3** presents the monthly cumulative solar irradiation and wind speed, along with the operating hours of each system.

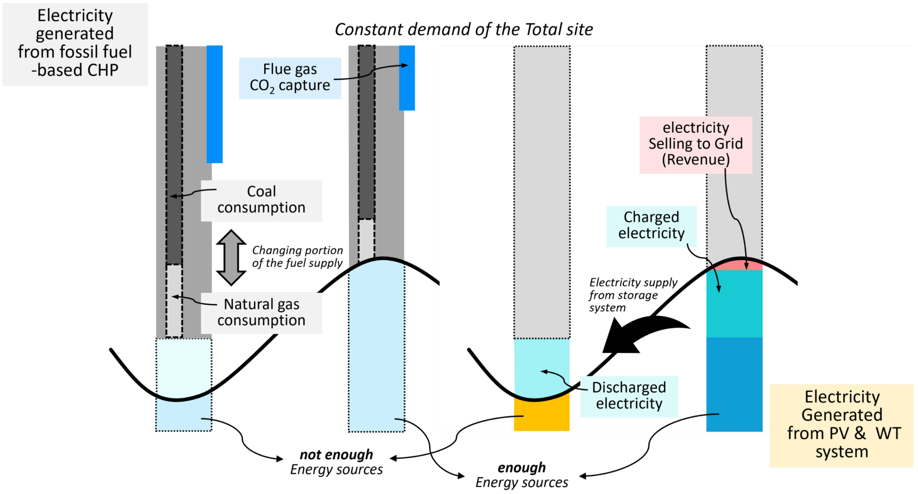

**Figure 2:** Research methodology for modeling and optimization of the integrated processes with a monthly basis.

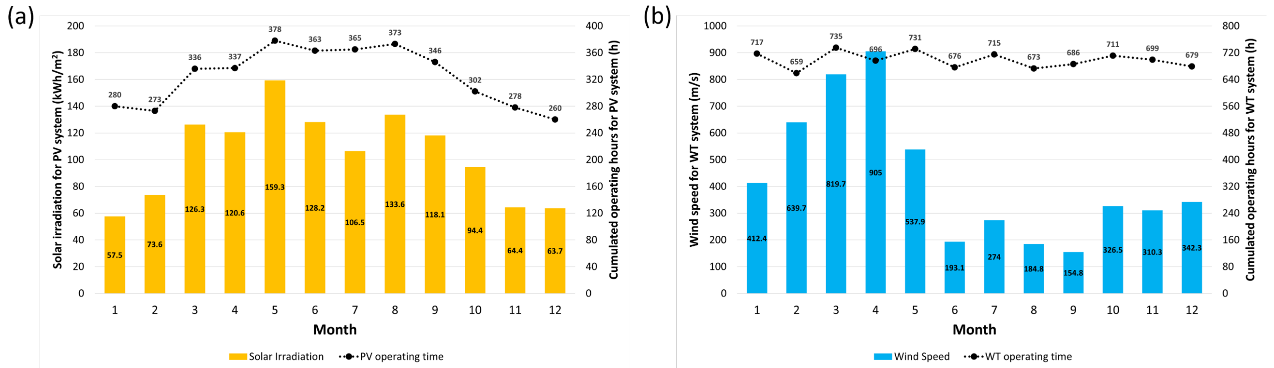

**Figure 3:** Monthly weather data for the analysis of (a) Solar irradiation and operating hours for PV system and (b) Wind speed and operating hours for WT system.

**Figure 4** illustrates the monthly optimized results of the integrated process under \$20/tCO$_2$ of carbon tax. Each month fully meets the Total site electricity demand of 68 MW, with fossil fuel-based systems contributing a significantly larger share than renewable systems. This is due to the lower costs associated with fuels and equipment in fossil fuel-based systems compared to the costs of renewable systems. In particular, during March and April, the higher electricity generation from the WT system leads to a substantial increase in the overall cost of the integrated utility. Therefore, it is observed that the fossil fuel-based system is chosen as the only operating system. Compared to the WT system, the PV system generates less electricity for the same plant area. Consequently, the contribution of the PV system to the site demand remains relatively small.

Although renewable electricity does not make up a large portion of the total power supply, the results in **Figure 4** (a) highlight the contribution of the integrated processes optimization. Renewable electricity can replace between 4.78% and 34.32% of the total site electricity demand each month, confirming the effective validation of the preliminary stage of the integrated utility process design and supporting the goal of establishing renewable energy-based electrification. This variation trend directly influences the system cost, as shown in **Figure 4** (b). The annualized cost of the utility process serves as the base case for comparison with the monthly optimized results. The cost reduction is primarily attributed to the WT system within the renewable energy system, which plays a dominant role in the optimization. The annualized cost in May shows the largest decrease of 5.53%, driven by peak renewable electricity generation, compared to the base case. The optimization also contributes to a 2.67% reduction in the annual cost of the integrated overall processes, with the price portion of the fossil fuel-based system decreasing by 6.15%.

The CO$_2$ emissions from fossil fuels account for the majority of the carbon tax, as shown in **Figure 4** (b). This is because the smaller emission per unit of electricity generated by renewables, along with the lower energy output from the renewable systems, leads to different optimization results concerning the ratio of renewable energy to fossil fuel-based systems. **Figure 5** shows the impact of carbon tax on integrated process optimization through sensitivity analysis. As carbon tax increases, the

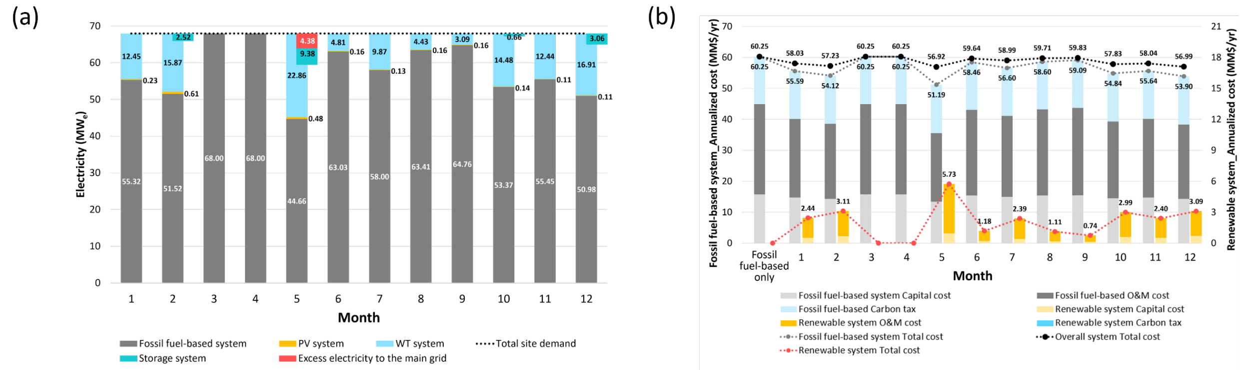

**Figure 4:** Monthly optimized results of integrated utility processes under \$20/tCO$_2$ of carbon tax. (a) Electricity generated from each system (b) Annualized cost breakdown.

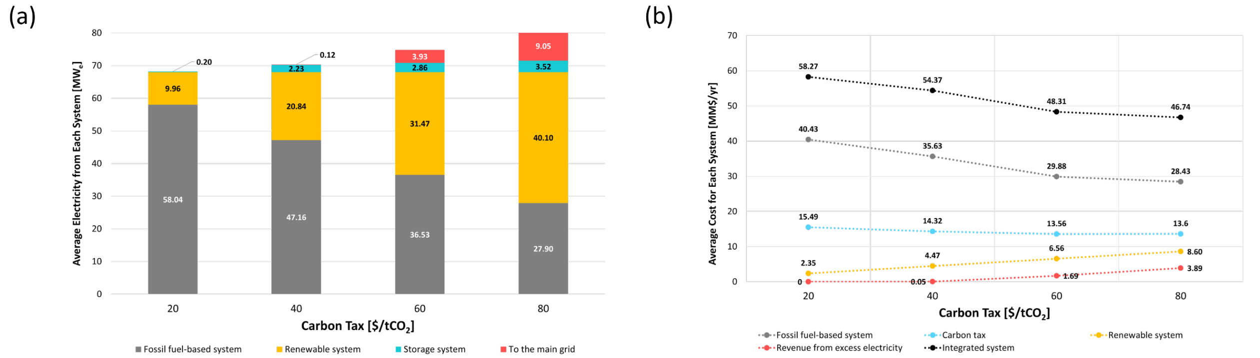

**Figure 5:** Average optimization results for the sensitivity analysis in carbon tax. (a) Electricity breakdown for each system and (b) Average annualized cost for each system.

portion of renewable electricity in the overall system grows due to the increased penalty for fossil fuel consumption. Accordingly, the cost of each system also changes in the same trend with electricity breakdown, and the cost of integrated processes ultimately decreases, as shown in **Figure 5** (b). At a 4 times increase in carbon tax, average overall system cost is reduced about 19.7%, highly affected by about 29.7% decrease of fossil fuel-based system.

## CONCLUSION

This study demonstrates the successful integration of renewable and $CO_2$ capture processes with conventional utility processes as an industrial decarbonization strategy. The optimization framework effectively addresses efficient management in process industries, providing a practical method for balancing economic sustainability with environmental improvement during the transition toward a fully renewable-based system.

If renewable systems with improved cost competitiveness are considered in the future, their increased contribution to the system's power demand could reduce fossil fuel consumption and the additional energy required for the carbon capture process, leading to lower $CO_2$ emissions across the overall processes. Furthermore, this approach mitigates the vulnerability to price fluctuations of fossil fuels on the international market, enhancing the cost stability of process operation through renewable energy integration.

Future work will focus on expanding the current framework to incorporate other renewable technologies. In particular, introducing the CSP system from the perspective of heat integration could add complexity, making it challenging to optimize steam demand across renewable energy with thermal energy storage and existing utilities. Moreover, sensitivity analysis on various costing parameters would provide valuable insights for planning decarbonized industries.

## ACKNOWLEDGEMENTS

This work was supported by the National Foundation of Korea under the framework of international cooperation program (No. 1711200829, FY2023), grant funded by the Korea government(MIST) (RS-2025-00515836), and the German Research Foundation (DFG) under the OPTIMGRID project (AE707 5-1).

## REFERENCES

1. International Energy Agency. $CO_2$ Emissions in 2022, IEA (2023) https://www.iea.org/reports/co2-emissions-in-2022
2. Metz B, Davidson O, Coninck Hd, Loos M, Meyer L. Carbon Dioxide Capture and Storage. Intergovernmental Panel on Climate Change (2005)
3. Park H, Kim J-K, Yi SC. Optimization of site utility systems for renewable energy integration. *Energy* 269:126799 (2023) https://doi.org/10.1016/j.energy.2023.126799
4. Sidnell T, Clarke F, Dorneanu B, Mechleri E, Arellano-Garcia H. Optimal design and operation of distributed energy resources systems for residential neighbourhoods. *Smart Energy* 4:100049 (2021) https://doi.org/10.1016/j.segy.2021.100049
5. Schemitt T, Leptinsky S, Turner M, Zoelle A, Woods M, Shults T, James R. Fossil energy baseline revision 4a. National Energy Technology Laboratory (2022) https://doi.org/10.2172/1893822